PHOTOVOLTAIC CELLS IN LOW-LIGHT OPERATION

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Abstract: Comparison of the properties of respective technologies shows that for low-light operation there are most advantageous inorganic thin film cells. It is very important to consider the operating conditions and adapt the selection of the photovoltaic cell to these conditions. Because of very small area of the cell needed for the low energy converters the price of the photovoltaic cell is not an important item in the total cost of an Enargy Harvesting converter. Simple and reliable low price JFET driven DC to DC converter was designed for this application.

Keywords: *Energy harvesting, Photovoltaic cell, low-light operation, low energy DC to DC converter.*

1 INTRODUCTION

When using photovoltaic converters for energy harvesting, it is necessary to consider a large range of light intensity and the wavelength from which a photovoltaic cell can absorb incident photons. The wavelength from which a photovoltaic cell can absorb incident photons depends on the width of Band Gap of semiconductors in the structure of the respective photovoltaic cell. The behavior of selected single cells under real operating conditions was tested for an EH converter operating at an energy level deep below 1 W. The low voltage at the cell output was boosted-up using the low voltage DC to DC converter.

2 PHOTOVOLTAIC CELLS IN LOW-LIGHT OPERATION

Low light operation difers substantially from the standard operation of photovoltaic cells. Usually the light intensity on a solar cell is measured in units known as 'suns', where 1 sun relates to standard illumination at AM1.5 (Air Mass factor) with incident radiation of 1 kW/m^2. This is good to compare different cells but it is very rarely found in real environment. In low light operation many other parameters are important as the bandgap of used semiconductor versus the spectral composition of the incident radiation, influence of the shunt resistance, working temperature of the cell and also the management of the energy on the output.

2.1 INTENSITY AND SPECTRAL DISTRIBUTION OF THE EXCITING RADIATION

Exitation of the electron to the conduction band requires energy given by the bandgap of respective semiconductor. The bandgap of crystaline silicon (E_G = 1.1 eV) corresponds to infrared light with a wavelength of about 1.1 microns. This means that only photons from red, yellow and blue light and some near-infrared part of spectra will contribute to photovoltaic power productiont. In case of high energy photons the excitated electron has an exces of energy and travels in the crystal latice until this energy is absorbed and thus the exces of photon energy changes o the heat. Consequently solar cell can convert only about 33,5 % of the incident sunlight energy, which is called the Shockley-Queissner limit [1]. Spectral composition of the incident radiation is therefore very important. Spectral composition of the incident light may considerably change in different conditions. For example, in direct sunlight, great part of radiated energy is in red and infrared part of the spectra. Crystalline silicon cells, which have the maximum absorption just in infrared and red part, are suited for this case but it can be also see from Fig. 1. and Table 1. that the optimal bandgap value have the solar cells based on CGCIS. At cloudy sky diffused radiation prevails and the spectral distribution is shifted toward shorter wavelengths. Radiation in the field of visible part of spectra will also prevail in case of indoor applications. Here the semiconductors with wider Band Gap are preferred.

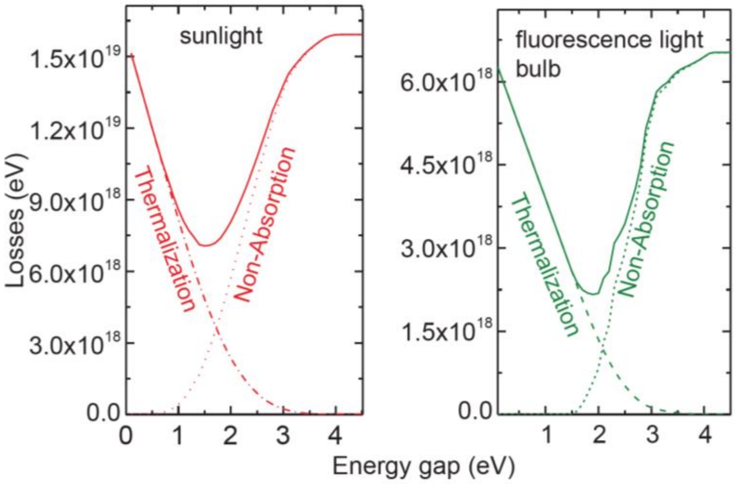

Figure. 1: Thermalization, non-absorption and total losses depending on the energy gap [2].

From Fig.1 it is obvious that the optimal bandgap for the sunlight application is about 1,5 eV, whereas for indor application the respective bandgap should be about 2 eV.

2.2 PHOTOVOLTAIC CELLS IN LOW-LIGHT OPERATION

The light dependence of generated voltage on the Si photovoltaic cell and its current and power is in Fig. 2a). It is evident that the current supplied by the cell is approximately linearly proportional to the illumination. The dependence of the voltage generated by the cell on the illumination is approximately logarithmic. Changing the intensity of light radiation will therefore primarily reflect the change in the current of the cell.

The open circuit voltage is given by equation $V_{0C} = \frac{nkT}{q} ln\left(\frac{I_{PH}}{I_0}\right)$ (1)

Here n is emission coefficient, k is Boltzman constant, T is temperature, q is charge of electron, I_{PH} is photocurrent and I_0 is saturation current of the cell junction.

Because of logarithmnis dependence of the opencircuti voltage on the light intensity the shift is approximately 100 mV for one order drop in the light intensity. Consequently even at very low intensity of incident radiation the voltage on the cell will still be a few tenths of a Volt.

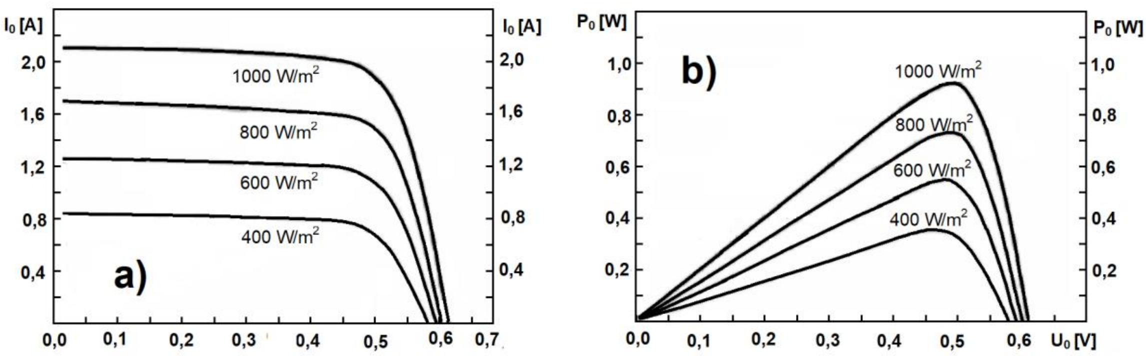

Figure. 2: **a)** A-V characteristics of the silicon photovoltaic cell
b) The power extracted from the cell

From Fig. 2b) it is obvious that there is an optimal voltage and current value for the maximum output of the cell. The voltage at which maximum power is reached decreases with light intensity very slowly.

For an ideal solar cell the series resistance equals zero while the shunt resistance equals to infinity. Low shunt resistance causes power losses in solar cells by providing a path for the light generated current. At very low light levels, the effect of the shunt resistance becomes important because the current flowing through the shunt resistance is taken from the photo-current which is generated by the photovoltaic process. The power loss could be much more than 10% .

2.3 PHOTOVOLTAIC CELLS FOR EH TRANSDUCERS

Crystalline or polycrystalline silicon photovoltaic cells are still standard cells with the price level at approximately 2 USD per Watt, depending on the size and technology. However, a comparison of the properties of respective technologies shows that for the intended application inorganic thin film cells are most advantageous, especially the cells based on amorphous and multicrystalline silicon, cadmium telluride (CdTe) and copper indium gallium selenide (CIGS or CIS). Thin film manufacturing technology also makes it easier to adapt to special requirements. Approximately 1% of material is required to produce thin-film structures compared to crystalline cells. Compared to crystalline cells there are about of a 30% less technological steps and the entire production process consumes about 50% of the ene

Amorphous silicon photovoltaic cells have the efficiency of energy conversion near 10 % but it rapidly drops in operation because of the light degradation process (Staebler–Wronski effect) to about 7 %. Nevertheless, amorphous silicon cells operate very well in low light conditions where the amount of produced energy could be comparable to crystalline silicon cells. Using non toxic silicon it represents one of the most environmentally friendly photovoltaic technologies. Silicon thin film cells are often prepared as a tandem of amorphous and microcrystalline cells with a different Band Gap. The overall efficiency is then higher - reaching the level about 13%.

The lab cell efficiency for CdTe and CIGS cells is beyond 21 % which is comparable to crystalline silicon cells. Cadmium teluride (CdTe) is very cost-effective but uses toxic cadmium. The usage of rare materials may also become a limiting factor to the large scale production. The Band Gap of CIGS cells varies continuously depending of content of indium and gallium from about 1.0 eV (CuInSe) to approximately 1.7 eV (CuGaSe).

TYPE	E_G [eV]	λ_0 [nm]	V_{OC} [V]	I_{SCA} [mA/cm^2]	η [%]	t_{EL} [years]
C - .Si	1,12	1107	≈ 0,65	≥ 30	≈ 20	≈ 20
Micro - Si	1,4	885	≈ 0,6	≤ 15	≈ 8-15	≈ 10-15
Perovskite	1,2- 2,3	1033 - 539	≈ 0,6 - 1,5	≈ 20	≈ 15	≈ ??
Amorph. Si	1,7	729	≈ 0,8	≤ 12	≈ 7-12	≈ 10-15
Amorph.Si +Micro-Si (tandem)	1,7 / 1,4	729 / 885	≈ 1,3	≤ 15	≈10 -13	≈ 10-15
CdTe	1,5	826	≈ 1,0	≈ 30	≤ 20	≈ 10-15
CGCIS	1,7 - 1,0	729 - 1240	≈ 0,8 - 0,5	≈ 30	≤ 20	≈ 10-15

Table 1: Most important parameters of examined photovoltaic cells with different technology: (E_G [eV] is Band Gap , λ_0 [nm] is Threshold Wavelength to the respective Band Gap, V_{OC}[V] is Open Circuit Voltage. I_{SCA} [mA/cm^2] is Short Circuit Current per area of 1 cm^2, η [%] is Efficiency of Energy Conversion, t_{EL} [years] is Expected Lifetime)

Perovskite solar cells have an ability to absorb light across almost all visible wavelengths and production technology is simple [4]. They have exceptional power conversion efficiencies which are after only a few years of investigation comparable to crystalline silicone cells, Despite that there are many challenges, the probability that the perovskite solar cells will be commercialized in near future is high. Organic photovoltaic cells, unfortunately, still remain only a promising technology. Although there are currently many convenient materials for organic cells, the degradation processes still pose a difficult problem [5].

2.4 ADDITIONAL COMPONENTS

For optimal use of low energy low voltage EH converter there is necessary to use a voltage converter with extremely low power supply voltage. Low voltage EH transducers therefore implement boost converter that requires only microwatts of power to begin the operation. As stated above, the cost of photovoltaic cells usually does not exceed 2 USD per Watt of maximum power depending on type of the cell, the currently used technology and volume of production. By full light an area of approximately 10cm x 10cm is required for 1 W of output power. However, for many applications (such as wireless sensors), the total daily power consumption of the device may be in order of several tens of milli-watt-hours. Then, even with very low light, we need much smaller cell area. The price of the respective photovoltaic cell can be therefore well below 1 USD and will not significantly affect the cost of the whole device. The price of the necessary DC/DC converter should not be much higher than the price of EH transducer alone. The unit price of low voltage integrated circuits for EH applications is around 2 USD and the price of other components included small SMT PCB could be also estimated at around 2 USD. Simple and reliable JFET driven converter suggested here has material and production costs significantly lower [6].

2.5 SINGLE J-FET DC TO DC CONVERTER WITH LOW CURRENT PREFORMANCE

To achieve higher efficiency the single JFET circuit shown in Figure 3 utilizes the energy stored in the transformer during the switch-on state.

1) As soon as the transistor turns on the secondary winding generates a voltage pulse. Capacior C_1 s being charged by means of this pulse. Once the transformer core becomes saturated the voltage on the secondary winding starts to drop. Due to the positive feedback given with actual polarity of primary and secondary windings the transistor closes. With a negative voltage on the capacitor C_1, JFET is maintained in a closed state until the next part of the cycle where it passes into the on-state and consequently the whole process is repeated. The voltage on the capacitor C_1 is at the same time output voltage of the converter as a whole.

2) As soon as the switch-off starts a voltage pulse appears on the primary winding, which charges the capacitor C_2. This is due to the drop of magnetizing current and subsequent collapse of the magnetic field in the transformer core.

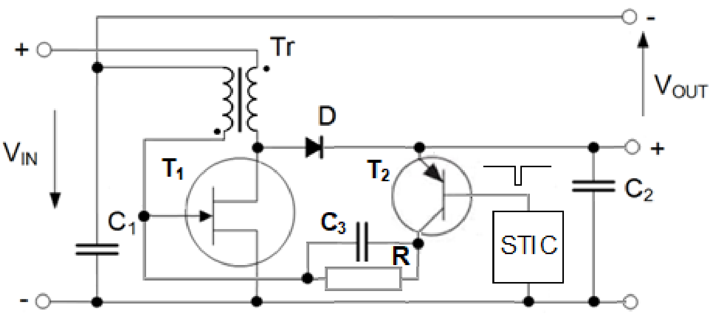

Figure 3: Low voltage converter with improved low-current performance

After interruption of the oscillation, the inverter is temporarily blocked by a negative voltage on the capacitor C_1. Then the voltage on the capacitor gradually decreases, thus enabling the inverter to start again. However, if the voltage at the collection capacitor (V_{IN}) does not rise above the start voltage, the drive current taken in the quiescent state may prevent further voltage increase on the collector capacitor and the inverter will not start. This situation can be avoided by means of start-timing circuit STIC. The voltage on the supercapacitor (or the battery) C_1 does not change after the oscillations end. The inverter is therefore permanently in a locked state and it does not take any current from the EH transducer. The starting impulse with a repeating interval adjustable within a few seconds is used to start the converter.

The energy to generate start-pulses is taken from an auxiliary source using the diode and the capacitor C_2 that is powered by the energy stored in the transformer core. When the transistor T_1 switches off there is a positive pulse on the primary winding of the transformer, diode D is open and the accumulated energy is moved to the capacitor C_1.

The starting impulse is made by charging the capacitor C_3 when the transistor T_2 is switched on. Resistor R connected in parallel with C_3 ensures that the "starting capacitor" C_3 is before each starting cycle discharged to zero voltage. The charge transmitted in each trigger pulse is therefore determined by the value of the capacitance of the "starting capacitor" C_3 and the voltage difference between capacitors C_1 and C_2.

3 CONCLUSIONS

Comparison of the properties of photovoltaic cells made by different technologies shows that for the intended application there are most advantageous inorganic thin film cells. It is very important to consider the operating conditions in which EH will work and adapt these conditions to the selection of the photovoltaic cell. Because of very small area of the cell needed for the low energy EH converters the price of the photovoltaic cell is not an important item in the total cost of an EH converter.

DC to DC converter able to operate from the voltage of few tenths of Volt was designed for this purpose. The output voltage could be in the level of several Volts and achieved efficiency of the apparatus is approximately 50%. Using the start-timing-circuit helps to extract the power from the photovoltaic cell even in the case of very low illumination.

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